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DRAG AND HEAT-TRANSFER COEFFICIENTS OF METEOR BODIES (I. Conditions of Weak Shielding)

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A70-20945 # Drag and heat-transfer coefficients of meteor bodies. I—Conditions of weak shielding (Koeffitsienty soprotivleniia i teploperedachi meteornykh tel. I—Usloviia slabogo zagorazhivaniia). V. N. Lebedinets, Iu. I. Portniagin, and A. K. Sosnova (Institut Eksperimental'noi Meteorologii, Obninsk, USSR). *Astronomicheskii Vestnik*, vol. 3, Oct.-Dec. 1969, p. 223-229. 8 refs. In Russian

Numerical calculation of the drag and heat-transfer coefficients of meteor bodies in the atmosphere, taking into account the shielding of the meteor surface by the repelled and vaporized molecules. The study is made for a free-molecule regime with allowance for the dependence of the effective diffusion cross section on velocity. Critical values of meteor dimensions are given at which the shielding effect becomes significant. T.M.

Koeffitsienty soprotivleniya i teploperedachi meteornykh tel. I. Usloviya slabogo zagorazhivaniya (Drag and Heat Transfer Coefficients of Meteor Bodies. I. Conditions of Weak Shielding), by V.N.Lebedinets, Yu.I.Portnyagin and A.K.Sosnova. Astronomicheskiy Vestnik, 3, no. 4 (1969) 223-229.
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by

V.N.Lebedinets, Yu.I.Portnyagin and A.K.Sosnova

Results of numerical calculations of the drag and heat transfer coefficients of meteor bodies are given, with allowance for shielding of the leading surface of the body of molecules flying away and evaporating and for the reactive momentum effect.

During the motion of a meteor through the atmosphere the shielding of its leading surface by molecules evaporating and flying away leads to a reduction of the energy and momentum fluxes to the meteor's surface, i.e. to a reduction of the heat transfer coefficient Λ and the drag coefficient Γ. Approximate estimates of Λ and Γ under conditions of weak shielding (with allowance only for the first collisions of the evaporating or outgoing molecules) have been obtained by a number of authors[1-5]. In all these studies some simplifying assumptions were introduced, which degraded considerably the accuracy of the results (for example, no account was taken of the velocity distribution of the evaporating particles, and the energy and momentum transferred to the body by collisions with particles were assessed approximately). Moreover, in refs. 1-3 no allowance was made for the dependence of the effective diffusion cross section Q_d on the velocity of the colliding particles, and the value of Q_d was assumed to be the same at meteor velocities as under gas-kinetic conditions.

Below we report calculations of Λ and Γ free from the above-mentioned shortcomings. The first-collisions approximation is used, i.e. the solution is applicable in the case of weak shielding.

Method of calculation

Under the conditions of free molecular flow all molecules whose paths intersect the body collide with the latter and transfer their energy; this energy goes primarily on heating, melting, and evaporation of the meteor substance. A momentum transfer also takes place, as a result of which the meteor's flight is retarded. As the atmospheric density increases the collisions between molecules in front of the body become important. If over a distance of the order of the characteristic dimensions of the body the number of such collisions is small, the corresponding regime of motion is regarded as almost free-molecular. The motion of meteor bodies under such conditions was studied in refs.1-3. Fairly recently V.A.Perepukhov[6] developed a rigorous mathematical method for calculating the aerodynamic characteristics of bodies moving in the regime of almost free molecular flow. Following this method we shall estimate the drag coefficient Λ and the heat transfer coefficient for meteor bodies moving in an almost free molecular regime, taking into account the body's evaporation and the dependence of Q_d on the meteor's velocity.

Consider a meteor body consisting of a sphere of radius R_o. We choose a coordinate system in which the meteor is at rest while the air molecules fly toward it with a velocity v_∞. We further suppose that the surface temperature is the same at all points, the energy and momentum accomodation coefficient is equal to unity, and the velocity distribution function of particles flying away from the surface of the sphere is

$$f(v_T) = n_0(2\pi RT_0)^{-3/2}\exp\left(-\frac{v_T^2}{2RT_0}\right), \qquad (1)$$

where n_o and v_T are respectively the density and the velocity of the molecules flying away ($v_T \ll v_\infty$) and R is the gas constant. We shall consider the collisions between the molecules or atoms leaving the sphere's surface and air molecules coming toward the surface. We introduce spherical (ρ, θ, β) and Cartesian (x,y,z) systems of coordinates with the origin at the center of the sphere (Figure 1). Then the flux of molecules leaving in unit time a surface element $dF = R_o^2 \sin\theta d\theta d\beta$ in the direction ψ, φ within an element of solid angle $d\omega = \sin\psi \, d\psi \, d\varphi$, with velocities in the interval v_T, $v_T + dv_T$, will be

$$d\Phi = n_0 (2\pi R T_0)^{-3/2} \exp\left(-\frac{v_T^2}{2RT_0}\right) \times \\ \times v_T^2 \cos\psi \sin\psi \, d\psi \, d\varphi \, dv_T \, dF. \qquad (2)$$

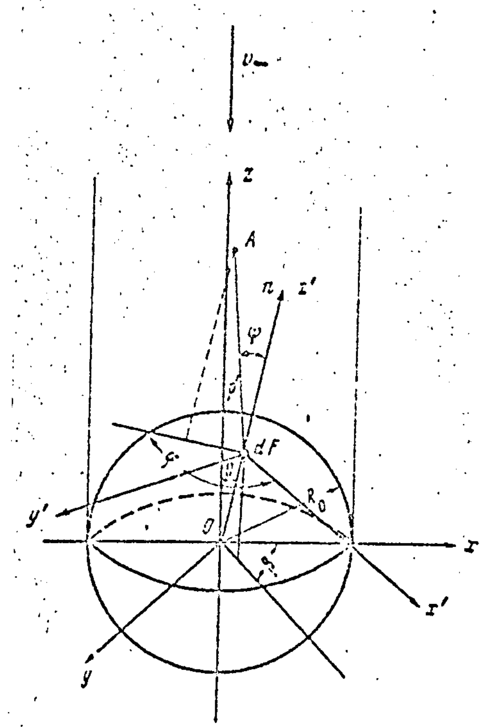

Figure 1 : Coordinate systems used in the calculation

The number of collisions between leaving molecules satisfying the conditions (2) and molecules of the incident flux in a volume element $\rho^2 d\rho \sin\psi \, d\psi \, d\varphi$ with the center at the point A(x,y,z) is:

$$
\begin{aligned}
K = {} & n_0 n_\infty (2\pi R T_0)^{-3/2} \times \\
& \times \exp\left(-\frac{v_T^2}{2RT_0}\right) v_T^2 \cos\psi \times \\
& \times \sin\psi \, d\psi \, d\varphi \, dv_T 2\pi\sigma^2 G_{21} \sin\nu \times \\
& \times \cos\nu \, d\nu \, d\mu R_0^2 \sin\theta \, d\theta \, d\beta \times \\
& \times \exp(-\rho/\lambda_{21}) \, d\rho.
\end{aligned}
\tag{3}
$$

where ν and μ are angles defining the directions of the line of centers of the colliding molecules (regarded as rigid spheres) in a coordinate system linked with the direction of the relative velocity G_{21}; $\lambda_{21} = v_T / n_\infty Q_d G_{21}$ is the mean free path of the leaving particles; n_∞ is the density of the incident particles; and $Q_d = \pi\sigma^2$ is the effective cross section for diffusion of the leaving molecules into the incident ones. Since $v_\infty \gg v_T$, $G_{21} \approx v_\infty$. If no evaporation is taking place, it follows from the law of particle conservation on the sphere surface that $n_o = 2n_\infty \sqrt{\pi} S_o' \cos\theta$, where $S_o' = v_\infty / \sqrt{2RT_o}$ is a dimensionless parameter. Expression (3) may be written in the form

$$
K = \pi R_0^2 n_\infty v_\infty f(\theta) f(v_T) f(\psi) f(\nu) f(\beta) f(\rho) f(\varphi) f(\mu) \, d\theta \, dv_T \, d\psi \, d\nu \, d\rho \, d\varphi \, d\beta \, d\mu, \tag{4}
$$

where

$$f(\theta) = 2\sin\theta\cos\theta,\ f(v_T) = 2(2RT_0)^{-2}\exp(-v_T^2/2RT_0)v_T^3,$$
$$f(\psi) = 2\sin\psi\cos\psi,\quad f(\nu) = 2\sin\nu\cos\nu, \tag{5}$$

$$f(\rho) = (1/\lambda_{21})\exp(-\rho/\lambda_{21}),\quad f(\varphi) = f(\mu) = f(\beta) = \frac{1}{2\pi}.$$

The distribution functions $f_i(x_i)$ in equations (4) and (5) are chosen so that

$$\int_0^{x_i} f(x_i)\,dx_i = \xi_i. \tag{6}$$

where the ξ_i are numbers distributed uniformly in the interval between zero and unity. With the aid of arbitrary sequences of random numbers distributed uniformly between zero and unity, equations (4)-(6) make it possible to obtain sequences of the parameters of collisions between incident and outgoing particles -- $v_T, \psi, \nu, \theta, \rho, \varphi, \mu, \beta$ -- with the appropriate probability densities, by formulas[6] :

$$v_T = \xi_{2i-1}K\sqrt{2RT_0},\quad \sin\psi = \sqrt{\xi_{i+1}},\quad \sin\nu = \sqrt{\xi_{i+2}},$$
$$\sin\theta = \sqrt{\xi_{i+3}},\quad \varphi = 2\pi\xi_{i+4},\quad \mu = 2\pi\xi_{i+5},\quad \beta = 2\pi\xi_{i+6}, \tag{7}$$

in which ξ_{i+k} are random numbers satisfying the conditions of (6). According to equation (1), one other condition is imposed on ξ_{2i-1} :

$$\xi_{2i} \leqslant \exp[-K_1(\xi_{2i-1})^2 + 3/2]\left(\sqrt{\frac{2}{3}}K_1\xi_{2i-1}\right)^3, \tag{8}$$

The interval of the change of the velocity modulus for molecules flying away in $0 - K\sqrt{2RT_0}$ (in the calculation we took $K_1 = 5$). When finding the formula for ρ it must be remembered that at meteor velocities

$Q_d = C/v_\infty$ (ref. 7), where $C = 1.7 \times 10^{-9}$ cm^3/sec. Then

$$\bar{\rho} = \frac{\rho}{R_0} = -\left[2\sqrt{2}\left(\frac{v_T Q_{d\infty}}{C} \right)\right] \mathrm{Kn}_\infty K_1 \xi_{2i-1} \ln(\xi_{i+7}), \qquad (9)$$

in which the Q_d^∞ are the effective diffusion cross sections of air molecules at a large distance from the moving body and

$\mathrm{Kn}_\infty = (2\sqrt{2} Q_d^\infty n_\infty R_o)^{-1}$ is the Knudsen number (ratio of the mean free path of the air molecules to the body's diameter). N collisions are considered with the aid of formulas (7) and (9) [the number N depends on the required accuracy of the calculation], the coordinates of each collision point being in each case found from:

$$\begin{aligned} x_0 &= [x' \cos\theta + (z' + R_0) \sin\theta] \cos\beta - y' \sin\beta, \\ y_0 &= [x' \cos\theta + (z' - R_0) \sin\theta] \sin\beta + y' \cos\beta, \\ z_0 &= [-x' \sin\theta + (z' + 1) \cos\theta], \end{aligned} \qquad (10)$$

where $x' = \rho\cos\varphi\sin\psi$, $y' = \rho\sin\varphi\sin\psi$, $z' = \rho\cos\psi$. If the point given by $M(x_o, y_o, z_o)$ is projected onto some point on the sphere surface, then at this point of the surface there is a loss of the following molecular characteristics:

$$\begin{aligned} &mv_\infty \quad \text{for the momentum flux in direction } v_\infty \\ \text{and } &\tfrac{1}{2}mv_\infty^2 \quad \text{for the energy flux} \end{aligned} \qquad (11)$$

where m is the molecular mass.

The quantity

$$D = [\sin^2 \nu z_0 - \sin \nu \cos \nu (x_0 \cos \mu + y_0 \sin \mu)^2] - [\sin^2 \nu z_0^2 - 2 \sin \nu \cos \nu z_0 (x_0 \cos \mu + y_0 \sin \mu) + \cos^2 \nu (x_0^2 + y_0^2 - R_0^2)] \tag{12}$$

gives the possibility of the intersection of particle trajectories after collision with the sphere. If $D > 0$, the particle collides with the sphere and transfers to it the following molecular characteristics:

$mv_\infty \cos^2 \nu$ for the momentum flux in the direction of v_∞ (13)

and $\frac{1}{2} mv_\infty^2 \cos^2 \nu$ for the energy flux

For the second particle in (11) $\sin \mu$ must be replaced by $-\sin \mu$, $\cos \mu$ by $-\cos \mu$, $\sin \nu$ by $\cos \nu$, and $\cos \nu$ by $\sin \nu$. Then, if $D > 0$, the second particle transfers to the sphere:

$mv_\infty \sin^2 \nu$ for the momentum flux in the direction of v_∞

and $\frac{1}{2} mv_\infty^2 \sin^2 \nu$ for the energy flux (14)

We must also take into account the reactive momentum of molecules evaporating or flying away, which for a single particle amounts to

$$mv \frac{z_o - R_o \cos\theta}{\rho}$$

where $\dfrac{z_o - R_o \cos\theta}{\rho}$ is the cosine of the angle between the direction of the thermal velocity vector and the z-axis.

For the summary characteristics it is sufficient to sum up the appropriate characteristics lost as a result of collisions and received by the sphere, and refer them to the total number of collisions.

R e s u l t s

If there is no evaporation only the air molecules flying away from the meteor body take part in shielding. In this case the heat transfer and drag coefficients will be written in the form

$$\begin{aligned} \Lambda &= \Lambda_{f.m.} + \Lambda_{(+)} - \Lambda_{(-)}, \\ \Gamma &= \Gamma_{f.m.} + \Gamma_{(+)} - \Gamma_{(-)}, \end{aligned} \qquad (15)$$

where $\Lambda_{f.m.}$ and $\Gamma_{f.m.}$ are the values of Λ and Γ under conditions of free molecular flow, $\Lambda_{(+)}$ and $\Gamma_{(+)}$ are increments to $\Lambda_{f.m.}$ and $\Gamma_{f.m.}$ due to the fact that some of the molecules after collision fly toward the meteor body, and $\Lambda_{(-)}$ and $\Gamma_{(-)}$ are corrections to $\Lambda_{f.m.}$ and $\Gamma_{f.m.}$ due to the fact that some of the air molecules directed at the body do not in fact reach its surface on account of collisions. Since at meteor velocities the accomodation coefficient $a \approx 1$ (ref. 5), in free molecular flow $\Lambda_{f.m.} = 1$ and $\Gamma_{f.m.} = 1 + \Delta\Gamma_{r.e.}$ where $\Delta\Gamma_{r.e.}$ is an increment due to the reactive effect of molecules flying away.

Putting $\Lambda_{(-)} - \Lambda_{(+)} = \Delta\Lambda_{s.e.}$ [*] and $\Gamma_{(-)} - \Gamma_{(+)} = \Delta\Gamma_{s.e.}$, we

[*] Translator's note: The Russian subscript "z.e.", translated here as "s.e.", is not defined; it has been assumed to indicate "shielding effect".

rewrite equations (15) in the form :

$$\Lambda = 1 - \Delta\Lambda_{s.e.},$$
$$\Gamma = 1 - \Delta\Gamma_{s.e.} + \Delta\Gamma_{r.e.} \qquad (16)$$

From equations (11), (13), and (14) it is not difficult to see that

$\Delta\Lambda_{s.e.} = \Delta\Gamma_{s.e.}$.

Values of $\Delta\Lambda_{s.e.}$ and $\Delta\Gamma_{s.e.}$ were calculated for various Knudsen numbers on a Minsk-2 computer. It was assumed that $\sqrt{2RT_o} = 1.5 \times 10^5$ cm/sec. To check the convergence of the calculation results with increasing number of collisions for each value of the Knudsen number we considered various numbers of collisions : 20,000, 40,000, 80,000, and 160,000. To exclude possible correlation between the ξ_{i+k}, where k = 0,1,....6,7, the numbers ξ_{i+k} were selected from various sequences of pseudorandom numbers supplied by a data unit. Without taking into account the dependence of Q_d on the velocity, $\Delta\Lambda_{s.e.}$ depends on two dimensionless parameters, Kn_∞ and S_o (ref. 6). Within the range of meteor velocities Q_d is inversely proportional to the velocity, and therefore in the absence of evaporation for meteor bodies $\Lambda_{s.e.}$ is velocity-independent, varying only with the parameter Kn_{∞}. The $\Delta\Lambda_{s.e.}$ values obtained by the present authors are given in Figure 2. A simple formula is obtained for $\Delta\Gamma_{r.e.}$:

$$\Delta\Gamma_{r.e.} = \frac{0.45}{S_0}. \qquad (17)$$

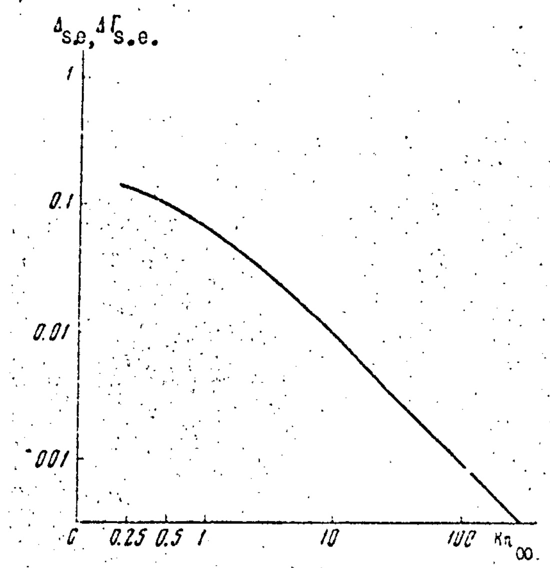

Figure 2 : Dependence of $\Delta\Lambda_{s.e.}$ and $\Delta\Gamma_{s.e.}$ on the Knudsen number, taking into account only shielding by the molecules flying off

After the beginning of intensive evaporation both the air molecules flying away and the evaporating molecules of meteor substance may take part in the shielding. If the entire energy received by the meteor is used up on its evaporation, the number of molecules evaporating for every incident air molecule is given by :

$$\gamma = \frac{\Lambda m v_\infty}{2\varepsilon} = \frac{\Lambda v_\infty^2}{2Q}, \tag{18}$$

where ε represents the evaporation energy of a single molecule of meteor substance and Q is the evaporation energy per gram.

In the general case the energy may be utilized not only on evaporation but also on heating of the meteor body and on blowing away of the molten skin, and it is then convenient to introduce a gasification parameter Π (ref. 8), which characterizes the proportion of energy going on evaporation. Then for every incident air molecule the number of molecules evaporating is equal to :

$$\Pi\gamma = \frac{\Pi\Lambda m v_\infty}{2\varepsilon} = \frac{\Pi\Lambda v_\infty^2}{2Q}. \tag{19}$$

From the above scheme of calculating $\Delta\Lambda_{s.e.}$ and $\Delta\Gamma_{s.e.}$ it is easy to see that, with allowance for evaporation, the formulas for Λ and Γ may be written in the form :

$$\begin{aligned} \Lambda &= 1 - (\Pi\gamma + 1)\Delta\Lambda_{s.e.} \\ \Gamma &= 1 - (\Pi\gamma + 1)\Delta\Gamma_{s.e.} + (\Pi\gamma + 1)\Delta\Gamma_{r.e.} \end{aligned} \tag{20}$$

From equations (19) and (20) we find the formulas for calculating Λ and Γ with allowance for screening by molecules evaporating and flying away :

$$\Lambda = \frac{1 - \Delta\Lambda_{s.e.}}{1 + \Pi r_\infty^2 \Delta\Lambda_{s.e.}/2Q}, \qquad (21)$$

$$\Gamma = 1 - \left(\frac{\Pi \Lambda r_\infty^2}{2Q}\right)\Delta\Gamma_{s.e.} + \left(\frac{\Pi \Lambda r_\infty^2}{2Q} + 1\right)\Delta\Gamma_{r.e.}$$

With the aid of equation (21) and the data of Figure 2 we obtained the dependence of the quantities $\Delta\Lambda = 1 - \Lambda$ and $\Delta\Gamma = 1 - \Gamma$ on the Knudsen number for three meteor velocities v_∞ (15, 30, and 60 km/sec) and for two values of Π : 0.5 and 1 (Figures 3 and 4).

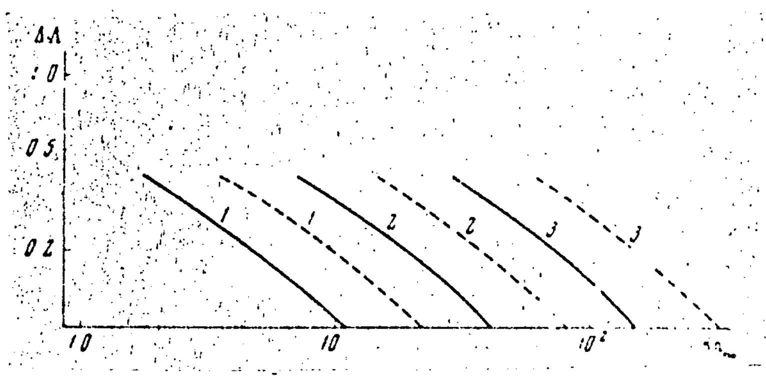

Figure 3 : Dependence of $\Delta\Lambda$ on the Knudsen number with allowance for shielding by particles flying away and evaporating, at various meteor velocities :
1 - v_∞ = 15; 2 - v_∞ = 30; 3 - v_∞ = 60 km/sec.
The continuous lines correspond to Π = 0.5 and the broken lines to Π = 1.0

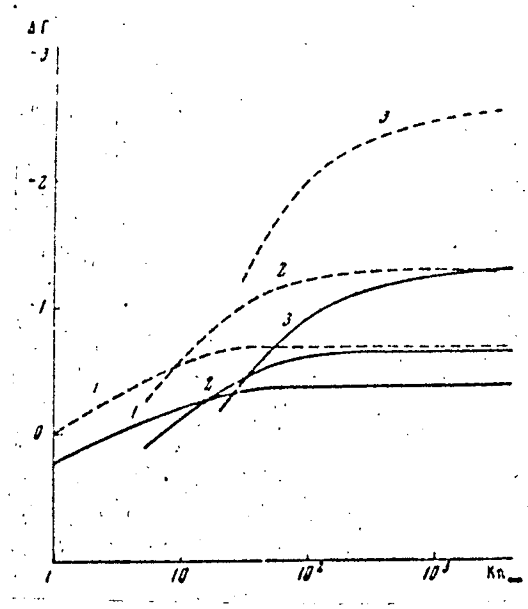

Figure 4 : Dependence of $\Delta\Gamma$ on the Knudsen number with allowance for the reactive momentum effect and for shielding by particles flying away and evaporating at various meteor velocities :
1 - v_∞ = 15; 2 - v_∞ = 30; 3 - v_∞ = 60 km/sec.
The continuous lines correspond to Π = 0.5 and the broken lines to Π = 1.0

The method described in this paper, taking into account only the first collisions, may be used to calculate Λ values between 1 and about 0.6.

Table

v,km/sec	$\Pi = 0$	$\Pi = 0.5$	$\Pi = 1$
15	0.1	1.8	3.5
30	0.1	7	14
60	0.1	28	56

The above table gives the critical Knudsen numbers corresponding to

$\Lambda = 0.6$ for various values of v_∞ and Π. Using the tabulated results and the formula $Kn_\infty = \lambda_\infty/2R_o$ (where λ_∞ is the mean free path of the air molecules), it is easy to find the limiting radius R_o of the meteor body in dependence on the meteor's velocity and altitude.

Comparison with the results reported in earlier publications[1-5] shows that the critical dimensions obtained in this paper for meteor bodies for which shielding by molecules flying away and evaporating is important are more or less mid-way between the approximate critical dimensions obtained in refs. 1 and 5.

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A b s t r a c t

Drag and transfer coefficients of meteor bodies have been calculated by a numerical method on a computer taking into account the shielding of

the leading surface by molecules flying away and evaporating and the reactive momentum of these molecules. The first-collisions approximation is used. Critical Knudsen numbers for which the drag and heat transfer coefficients can be calculated are given for various meteor velocities and gasification parameters.

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